Foster + Partners

Building Movable Dunes

BY ERIC FENSKE, S.E., AND PATRICK RAGAN

Using an iterative analysis, engineers let the structural design find its most efficient form.

THE PAVILION OF THE UNITED ARAB EMIRATES sits on one of the larges sites at the Expo 2010 in Shanghai. Designed by UK-based architect Foster + Partners, collaborating with Chicago-based structural engineer Halvorson and Partners (HP), it rises to a height of 20 m at its highest peak with a plan diameter of roughly 60 m. The pavilion encloses an area of approximately 3,900 sq. m of exhibition space, information areas, and back of house facilities, showcasing the past, present, and future of the United Arab Emirates through a series of interactive exhibits. After spending its time at Expo 2010 in Shanghai, the pavilion will be moved to a permanent site on Saadiyat Island in Abu Dhabi, United Arab Emirates.

Roof Form

Foster + Partners' architectural concept of the pavilion's roof surface was inspired by the sand dunes that dominate the area found in the United Arab Emirates' most famous desert, known as "The Empty Quarter." The roof resembles a series of three sand dunes; an individual large dune on the south side of the building and two smaller dunes on the north side. A low roof lies between the dunes and connects the interior spaces on the north and south sides. Cantilevered canopies extend from the dunes over the entrances at the north and south faces of the building.

After initially looking at the architectural surface, HP engineers divided the roof into four structural regions:

1. The curved parts of the roof (windward side of sand dunes).
2. The flat sloped parts roof (leeward side of sand dunes).
3. The low roof between the dunes.
4. The cantilevered canopies at the door openings.

To allow for flexibility in the main exhibition spaces, the interior space under each of the sand dunes is column free. To most effectively form the roof structure without columns the three windward sides of the dunes were treated as structural shells, each with unique boundary conditions. The shell structure is an efficient scheme to support the long-span, free-form roofs because it resists the applied forces through axial loads in the structural members rather than in bending.

Because the form of the structural shell is highly dependent on the support locations, the first step was to establish the boundary conditions for each of the dunes. On the east and west sides of the building the structure extends to the ground and is thus supported. Columns were provided only along the north and south sides of the building's perimeter and beneath the low roof running between the dunes. At the leeward sides of the dunes, long beams span between the top of the shells and the columns below. Finally, two girders were introduced on the north side, where the surface changes curvature, to support the reactions from the two smaller dunes, which behave as independent shells.

Once the boundary conditions of each dune were established,

Opposite page: Architectural rendering of the United Arab Emirates Pavilion for Shanghai's Expo 2010.

HP engineers analyzed the initial building surfaces developed by the architect and found that there were areas of the roof that did not perform well as structural shells. Essentially these regions were too "flat," and therefore had to carry the gravity load in bending, rather than axial load. This resulted in "soft spots" in the structure which are clearly visible in the initial deflection contours.

To find a more optimal shape, the engineers conducted an iterative nonlinear form-finding analysis on each of the three shells. Upward forces were applied to the shells in incremental fashion while maintaining the previously established boundary conditions. As the iterations progressed, the softer areas within the structure deflected upward significantly in comparison with the surrounding, stiffer areas. This process added curvature to the areas that were initially too flat, and allowed the structure to behave much more like a shell, and therefore more efficiently. The result of the analysis is that the structure "finds" its natural form as a shell, much the same as a slack rope finds its natural shape as a catenary.

At the conclusion of the form-finding analysis, the surface was exported and sent back to the architect who confirmed that the optimized shells maintained the design intent. Indeed, the aesthetic modification was quite subtle, with the largest nodal adjustment of 1.4 m being a small fraction of the overall building dimension.

Comparing the surface of the form-found analysis to the original surface illustrates that through minimal changes in shell profiles and curvature, the dunes perform substantially better as a shell, thus reducing the structure. For a given structural weight, the revised surface reduced the maximum deflections on the south shell by a factor of nearly 10.

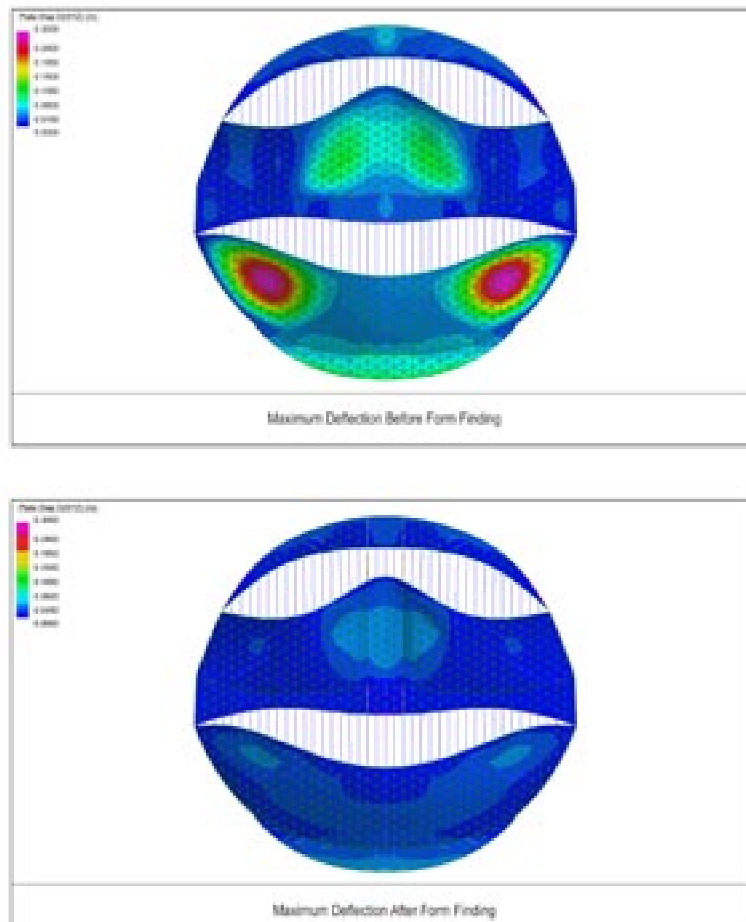
Structural Materials

A series of structural materials for the pavilion was investigated in parallel to the form finding exercises, including steel, reinforced concrete, timber, and even fiberglass. In addition to satisfying the applicable structural codes, the final material needed to achieve three main criteria; 1) to efficiently support the cladding system of the pavilion, 2) to minimize the structural depth in the dunes in order to maximize the volume of the interior spaces, and 3) to allow for the deconstruction of the pavilion after Expo 2010 and its reassembly in the United Arab Emirates. Structural steel was found to be the best material for the pavilion due to its high strength and stiffness and its use of demountable bolted connections.

The shell portions of the dunes, which face south, are opaque in order to reduce the sunlight entering the pavilion. Using triangular stainless steel cladding panels approximately 1 m in each side enabled the designers to achieve the appearance of the free-form curved surface while maintaining flat cladding elements. Each corner of each cladding panel needed to be supported by the primary structure below. A diagrid structural system following the cladding pattern was chosen to form the shell structures, but with a module of approximately 2 m on each side. Clad-

Celebrating Urban Life

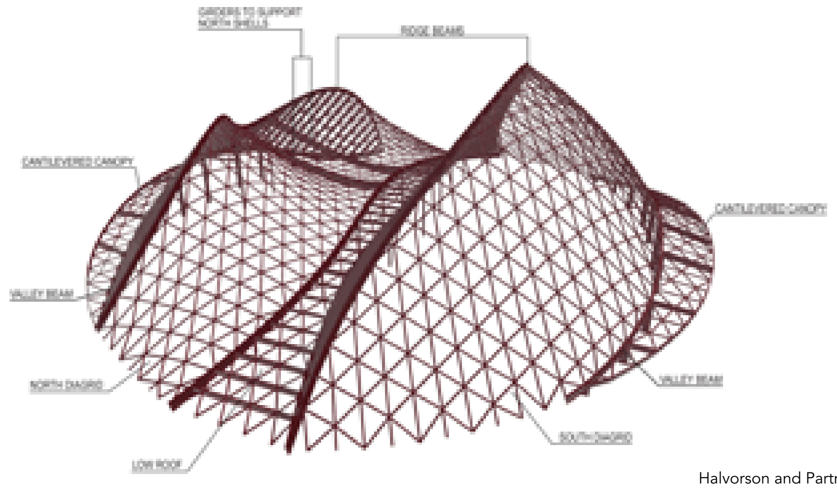
Shanghai, China's Expo 2010 opened May 1 and runs through October 31, 2010. Celebrating the theme "Better City, Better Life," the Expo is being staged along the waterfront area on either side of the Huangpu River. With approximately 192 countries and 49 international organizations participating, Expo 2010 is the largest in Expo history. Many participants constructed individual temporary pavilions illustrating their role within the theme.



Halvorson and Partners

Making minimal changes in shell profiles and curvature enabled the shell structure to perform substantially better, as shown in these plots of maximum deflections before and after form-finding analysis.

Eric Fenske, S.E., and Patrick Ragan are with Halvorson and Partners, Chicago. As senior project engineer Fenske led the U.A.E. Pavilion work. Ragan is a staff engineer and worked on the pavilion roof form-finding analysis.



Halvorson and Partners

After sizing the structural steel members, engineers exported the design into Microstation and used in-house script routines to produce 3D renderings of the structure for review by the architect.

ding supports were placed at each node of the diagrid as well as the midpoints of the structural members supporting each corner of the cladding. In addition, the diagrid is very stiff in plane and thus can perform well as a structural shell.

Engineers discretized the shell surfaces into the individual diagrid members using Rhino. The diagrid structure was then imported into Strand7 to size the structural members. A uniform depth of 200 mm structural steel members was found to meet the strength and stiffness requirements for the diagrid shells. Structural steel pipe forms the ridge beams at the transition between the windward and leeward sides of the dunes. Standard wide-flange sections form the beam columns at the leeward side of the dunes, the moment frames at the low roof between the sand dunes, and the columns and beams at the north and south faces. Additional diagonal wide-flange members were added at both the low roof and the cantilevered canopies to support the triangular pieces of cladding and stiffen these areas in plane.

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Making the Pavilion Demountable

The final step of the structural design was to work out the demountability of the pavilion. Most of the pavilion's steel connections are standard bolted connections, both the shear and moment connections. These can simply be unbolted after the Expo and reassembled in its new location. But the nodes of the diagrid shells were quite different.

For stability, nodes of the single-layer diagrid needed to have bending stiffness out of plane, but a traditional bolted connection is considered a hinge with no bending stiffness. Many other single-layer steel diagrids have welded nodal connections and possess out-of-plane bending stiffness, but they were not an efficient option in this case.

After researching various bolted diagrid nodes, engineers selected a proprietary node system from Menomonee Falls, Wis.-based Novum Structures. The company's free-form nodes use bolted connections that can carry out-of-plane moments. Using the bolted nodes, the entire structure can be demounted and rebuilt easily. Novum Structures ultimately was selected as the structural steel subcontractor for the diagrid. **MSC**

Owner
National Media Council, Dubai, United Arab Emirates

Design Architect
Foster + Partners, London

Structural Engineer
Halvorson and Partners, Chicago

Structural Steel Subcontractor–shell side
Novum Structures, Menomonee Falls, Wis. (AISC Member)

Structural Software
Rhino, Microstation, Strand7

Below: Using a proprietary bolted diagrid node simplified deconstruction of the entire structure at the close of the exposition for subsequent transport and reassembly.

Bottom of page: Erection of the pavilion's steel superstructure began in May 2009 and was completed in August 2009.